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ASTRONOMY AND ASTROPHYSICS

New infrared object in the field of the SMC cluster NGC 330*

A. Kučinskas[1,2,3] **, **V. Vansevičius**[4], **M. Sauvage**[5], and **T. Tanabé**[6]

[1] National Astronomical Observatory, Tokyo, 181-8588, Japan
[2] Institute of Theoretical Physics and Astronomy, Goštauto 12, Vilnius 2600, Lithuania
[3] Institute of Material Research and Applied Science, Vilnius University, Čiurlionio 9, Vilnius 2009, Lithuania
[4] Institute of Physics, Goštauto 12, Vilnius 2600, Lithuania
[5] CEA/DSM/DAPNIA/Service d'Astrophys. C. E. Saclay, F-91191 Gif-sur-Yvette Cedex, France
[6] Institute of Astronomy, School of Science, The University of Tokyo, Tokyo, 181-8588, Japan

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Abstract. We report ISO (Infrared Space Observatory) observations of a new infrared source discovered in the vicinity of the young populous cluster NGC 330 in the Small Magellanic Cloud. The object was observed with ISOCAM at 4.5, 6.75 and 11.5 μm and shows a prominent mid-infrared excess, indicating the presence of a dust shell. The available observations of the optical counterpart together with the mid-infrared ISOCAM data suggest that this object is most likely a post-AGB star, or a Be supergiant. Cluster membership and candidate evolutionary scenarios are discussed briefly.

Key words: ISO satellite: ISOCAM – Magellanic Clouds: SMC – Infrared: stars – Stars: emission-line, Be – Stars: AGB and post-AGB

1. Introduction

NGC 330 is a young (~10-50 Myr, Chiosi et al. 1995, Cassatella et al. 1996; Keller et al. 1999b) populous cluster in the Small Magellanic Cloud (SMC). An intriguing property of this cluster is its richness in Be star content (Grebel et al. 1992; Keller et al. 1999c). The Be phenomenon is observed in objects with very different evolutionary states, such as classical Be stars, Herbig Ae/Be objects, Be supergiants, symbiotic stars or post-AGB objects (see e.g. Zickgraf, 1998). Since the age of NGC 330 is $\leq$ 50 Myrs, some of the Be stars 'observed in this cluster can indeed be classical Be stars, Be supergiants or even Herbig Ae/Be stars. On the other hand, stellar evolution theory predicts that at the age of ~50 Myr high mass stars ($M_\star > 7M_\odot$) should already reach the AGB stage (Fagotto et al. 1994). Since the lifetime of such massive objects on the AGB is very short, possibly less than a few 10^6 years (Blöcker, 1995), some of the objects showing the Be phenomenon in NGC 330 can be thus expected to be massive post-AGB stars.

Additional information helping to distinguish between these different evolutionary groups of Be stars can be obtained from the observations in the infrared. Except possibly for the classical Be stars, strong emission at infrared wavelengths is typical for most objects showing the Be phenomenon, including Herbig Ae/Be stars, Be supergiants, post-AGB objects and symbiotic stars. Each of these groups can be characterized by different circumstellar properties, such as the dust column density, dust temperature and composition, and so forth (Waters et al. 1998). Indeed, most of these quantities can be constrained from mid-IR observations.

In this work we present the ISOCAM observations of a new infrared source, which is the most prominent in the field of NGC 330 at mid-IR wavelengths. This object appears to be a strong Hα emission source and thus can represent a possible Be star candidate. Employing ISOCAM observations and data available from the literature we discuss the properties of this object and consider several alternatives for constraining its evolutionary status.

2. Observations and results

The new mid-infrared object (MIR1) was discovered during the raster imaging observations of the populous cluster NGC 330 with the ISOCAM (Cesarsky et al. 1996) on board the ISO satellite (Kessler et al. 1996). Observations were made on May 22, 1997 using the broad-band CAM filters LW1, LW2 and LW10, corresponding to the effective wavelengths of 4.5, 6.75 and 11.5 μm, respectively. The raster mode was 5 × 5, with a raster step size equal

Send offprint requests to: A. Kučinskas

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Table 1. Optical and mid-infrared photometry of MIR1

B mag	V mag	I mag	LW1 (mJy)	LW2 (mJy)	LW10 (mJy)
17.63[1]	17.13[1]	16.32[1]	4.7 ± 1.4	12.6 ± 0.4	32.0 ± 0.5

[1] optical data are averages from the following sources : Balona 1992; Keller et al. 1999c; Sebo & Wood 1994; Vallenari et al. 1994.

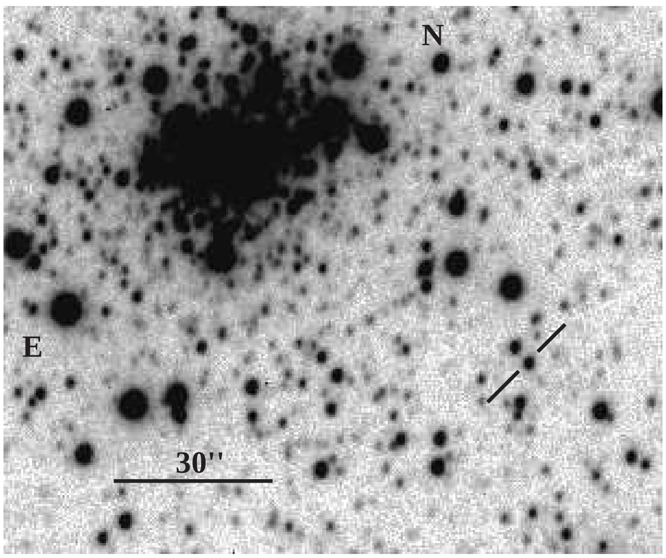

Fig. 1. Identification chart of MIR1 in I-band (north is up and east is left). The frame also covers the central part of SMC cluster NGC 330.

to 8 pixels (24″) and a pixel field of view (PFOV) of 3″. The fundamental integration time was set to $t_{\rm int} = 2.1$ sec, with a total number of about 15 exposures per single raster position. ISOCAM data were reduced using the CAM Interactive Analysis software (CIA version 3)[1] and the photometry was performed with the IRAF APPHOT package.

The measured mid-IR fluxes, together with the optical photometry collected from the literature, are given in Table 1. The ISOCAM flux errors given in Table 1 are formal APPHOT errors. The absolute photometric uncertainty of the ISOCAM measurements is estimated to be less than 20% (Biviano, 1998).

The optical counterpart of the infrared source was identified from the instrumental coordinates of MIR1 which were derived with respect to the positions of 8 field stars on LW2 CAM frame (identification accuracy is $\sim 1''$). The identification chart of MIR1 is given in Fig. 1.

[1] The ISOCAM data presented in this paper was analyzed using "CIA", a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A., France.

3. Discussion

The optical counterpart of MIR1 appears to be the variable star 224 discovered by Balona (1992). During the observing run of six nights when it was monitored by Balona, it faded by 0.2 mag and was distinctly variable within a night. Although periods around the 1 day expected for a Cepheid were indicated, no period gave a satisfactory fit to the data so the observed scatter and red color led Balona to suspect that it may be a double mode Cepheid on the red edge of the instability strip. Independent observations of NGC 330 (Sebo & Wood 1994) made over a 4 year period verified the variability of MIR1 (their star 515V)with a $\Delta V \approx 0.5$ and $\Delta I \approx 0.4$, but again no regular period was evident. Strikingly, the average V magnitude over six days (17.12; Balona, 1992) is very similar to the average V magnitude over ∼4 years (17.17; Sebo & Wood, 1994).

The optical counterpart of MIR1 was found to be a strong Hα source. Observations in the narrow-band ($\Delta\lambda = 1.5$nm) Hα filter showed that this object (star 485, Keller et al. 1999c) was the second strongest Hα emitter in the field of NGC 330 after the planetary nebula L305. This object is also listed in the SMC Hα source catalog of Meyssonnier & Azzopardi (1993) as object 906.

The strong Hα emission and the prominent mid-IR excess are difficult to assess within the evolutionary scenario of a classical Cepheid. Indeed it is possible that this object is a binary system, however the discussion of this possibility in the view of the scarce observational facts seems rather premature. The (H$\alpha - R$) color index is much larger in MIR1 than in any classical Be star in NGC 330 (Keller et al. 1999c), which, together with a strong mid-IR excess, indicates that MIR1 is unlikely to be a classical Be star. Therefore, we will further concentrate on the Be supergiant, Herbig Ae/Be and post-AGB star scenarios instead.

3.1. Be supergiant and Herbig Ae/Be star scenarios

One of the possible alternatives for constraining the evolutionary status of MIR1 is a Be supergiant scenario. This is indeed supported by the existence of Hα emission, which is typical to all types of Be stars. Spectral observations of MIR1 obtained by Keller (1999a) confirm that this object is a very strong Hα emitter; the spectrum clearly shows Hα line though no Hγ or higher.

Although the observed optical color indices of MIR1 are distinctively different from those of Be supergiants in the Magellanic Clouds (Zickgraf et al. 1992), this may be a consequence of the interstellar or circumstellar reddening. A dereddening procedure employing the reddening-free Q parameter yields $Q_{BVI} \approx -0.09$ (calculated assuming the standard excess ratio) which indicates that the spectral type of this object (depending on the luminosity class) should be O8-B2. Taking B0 as a representative of these values, one obtains $V_0 \sim 14.60$, $(B-V)_0 \sim -0.30$ and $(V-I)_0 \sim -0.27$, $A_V \sim 2.5$ and, using the SMC distance

modulus of 18.9, $M_V \sim -4.3$. Assuming that the bolometric correction for the spectral type B0 is $BC_V \sim -2.5$, we derive $M_{\rm bol} \sim -6.8$. Taking into account the errors of the spectral type determination (which set a range of possible $T_{\rm eff}$ between $20\,000 - 34\,000$ K), the obtained $T_{\rm eff}$ and $M_{\rm bol}$ are indeed comparable with those of Be supergiants in the MCs (cf. Zickgraf et al. 1992). Keller et al. (1999b) show a HR diagram of the cluster from the HST data and the Be stars at the cluster turnoff have $T_{\rm eff} \sim 16\,000$ and $M_{\rm bol} \sim -5.8$. They also have one Be star (B13) like a blue straggler with $T_{\rm eff} \approx 32\,000K$ and $M_{\rm bol} \sim -6.5$. These temperatures and luminosities are similar to the ones obtained for MIR1. The derived $A_V \sim 2.5$, however is much higher than the average in the field of NGC 330 (which measures the range from $E(B-V) = 0.03$ derived by Carney et al. (1985) to $E(B-V) = 0.12$ obtained by Bessell, 1991), and therefore indicates a significant circumstellar extinction.

Indeed, the spectral energy distribution of MIR1 shows a strong mid-IR excess (Fig. 2). The estimate of the ratio of ISO LW10 band flux over the V band flux in MIR1 yields $F_{12}/F_V \sim 3.3$. This is comparable with the $F_{12}/F_V \sim 5.4$ observed in a 'representative' Be supergiant GG Car (Waters et al. 1998) and thus could be viewed as an additional argument supporting the Be supergiant scenario.

Employing theoretical evolutionary tracks of Fagotto et al. (1994) and making use of the derived $T_{\rm eff}$ and $M_{\rm bol}$ we obtain a stellar mass of $M_\star \sim 15 - 20 M_\odot$ and the age of 8-14 Myr. The derived age of MIR1 is comparable with the cluster's age (10-20 Myr, Cassatella et al. 1996), suggesting that the candidate Be supergiant could be a cluster member.

Prominent mid-IR excesses are also common in Galactic Herbig Ae/Be stars with cool circumstellar shells (group II objects, see Hillenbrand et al. 1992). However, Herbig Ae/Be scenario seems rather unlikely for the case of MIR1. First, the available observations of NGC 330 do not show any evidence for the ongoing star formation in the field of NGC 330. Second, although some Galactic Herbig Ae/Be stars are observed as isolated objects, they are usually low-mass stars (cf. Hillenbrand et al. 1995) and therefore the high mass of the possible Herbig Ae/Be candidate ($\geq 25\ M_\odot$) inferred from the dereddened photometry of MIR1 and the SMC distance modulus rules out this possibility too.

3.2. Post-AGB star scenario

Post-AGB stars have been long recognized as one of the evolutionary groups showing the Be phenomenon. Indeed, strong Hα emission is typical for most post-AGB objects and thus the existence of Hα emission in MIR1 works in favor of this scenario too.

Most of the post-AGB objects show a double-peaked spectral energy distributions (e.g., Kwok, 1993; Zhang

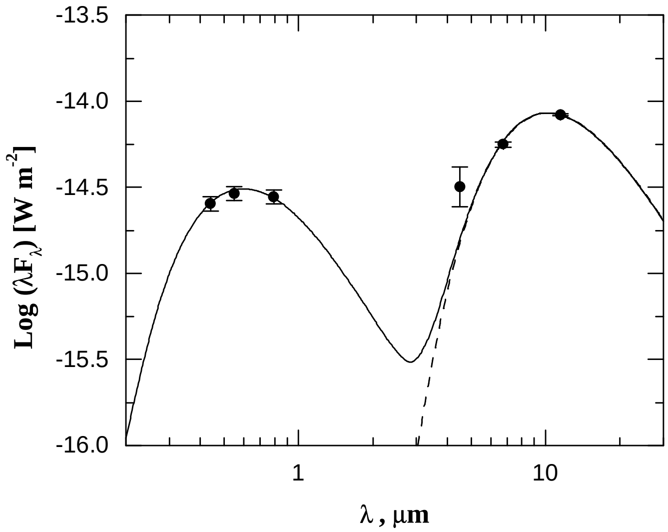

Fig. 2. Spectral energy distribution of MIR1, constructed from optical photometry and ISO data (Table 1). Error bars of the mid-IR data are formal IRAF/APPHOT errors. Solid line shows two-blackbody fit to the optical and mid-IR data ($T_{\rm BB_1} = 6200$ K and $T_{\rm BB_2} = 360$ K); dashed line indicates $T_{BB} = 360$ K fit to the mid-IR ISOCAM data used to estimate the infrared luminosity $L_{\rm IR}$ (see text for details).

& Kwok, 1991), similar to the one observed in MIR1 (Fig. 2). A simple estimate of the infrared luminosity obtained from the blackbody fit to the ISOCAM data yields $L_{\rm IR} \sim 1300 L_\odot$ with a blackbody dust temperature $T_{\rm d} = 360$ K. The estimate of the dust mass in the circumstellar shell, $M_{\rm d}$, can be made then using the following expression (Gurzadyan, 1997) :

$$\frac{M_{\rm d}}{M_\odot} = 9.21\, T_{\rm d}^{-4}\, \frac{L_{\rm IR}}{L_\odot} \qquad (1)$$

where $T_{\rm d}$ and $L_{\rm IR}$ are the dust temperature and the infrared luminosity, respectively. Taking the $L_{\rm IR}$ and $T_{\rm d}$ values derived above, one obtains $M_{\rm d} \sim 7 \times 10^{-7} M_\odot$, which is comparable with the dust masses typical for the post-AGB objects (e.g., Pottasch & Parthasarathy, 1988). Two facts should be noted, however. Firstly, the obtained blackbody dust temperature ($T_{\rm d} = 360$ K) can be considerably overestimated, since its derivation relies on the mid-IR data only and does not take into account any information about the dust radiation at longer wavelengths. Secondly, at the dust temperatures typical for the post-AGB objects, a large fraction of infrared flux is emitted at wavelengths longer than $\sim 12\mu$m and thus $L_{\rm IR}$ can be considerably higher than the presently derived value. Therefore, the obtained estimate of $M_{\rm d}$ indicates only a lower limit for the dust mass in MIR1.

The upper limit for the effective temperature of the central star of the possible post-AGB object can be inferred from the following considerations. If MIR1 is as-

sumed to be a normal planetary nebula (i.e., past the PPN stage), the effective temperature of the central star should be at least $T_{\rm eff} \sim 30\,000$ K and the observed $(B-V) = 0.50$ would indicate a considerable circumstellar extinction. Indeed, the central star with $T_{\rm eff} \sim 30\,000$ K should have $(B-V)_0 \sim -0.30$, and hence the $E(B-V) \sim 0.8$, that is, $A_V \sim 2.5$ and $M_V \sim -4.0$. Assuming that the bolometric correction is $BC_V \sim -3.0$ one obtains $M_{\rm bol} \sim -7.0$, which is very close to the classical luminosity limit for the post-AGB stars ($M_{\rm bol} \sim -7.2$, e.g. Shaw & Kaler, 1989). Thus we conclude, that the classical luminosity limit for the post-AGB objects sets the upper limit for the effective temperature of the central star at about 30 000 K.

The lower limit for the effective temperature of MIR1 can be constrained from the observed SED. The two-blackbody fit to the optical and mid-IR data (see Fig. 2) gives a lower limit estimate of the total luminosity of MIR1, $L_{\rm tot} \sim 1800 L_{\odot}$. Using a simple iteration procedure one can obtain the $(B-V)_0$, and therefore $T_{\rm eff}$, which would produce the observed $L_{\rm tot}$ with the observed $M_V \sim -1.8$. Such procedure yields $(B-V)_0 \sim -0.14$, $A_V \sim 2.0$, and $T_{\rm eff} \sim 14\,000$ K, seting this as a lower limit for the effective temperature of the central star.

The obtained temperature range suggests that MIR1 can be a good proto-planetary nebula (PPN) candidate. This is reinforced by the fact, that the infrared to the total luminosity ratio in MIR1 is $L_{\rm IR}/L_{\rm tot} \sim 0.7$, which is considerably higher than the value typical for the planetary nebulae ($L_{\rm IR}/L_{\rm tot} \sim 0.3$, see e.g. Pottasch, 1997). Since the presently estimated total luminosity of MIR1 is only $L_{\rm tot} \sim 1800 L_{\odot}$, it is rather unlikely that this object could be a high mass post-AGB star belonging to NGC 330; instead, it is probably a low mass field star. However, the mass and thus the evolutionary status of the possible PPN can not be constrained precisely yet. Therefore the tighter constraints on this scenario should be set by future optical spectroscopy of MIR1, which would provide additional information both about the central star and the nebula.

4. Conclusions

We present the ISOCAM observations of a new infrared object in the field of the young populous cluster NGC 330 in the Small Magellanic Cloud. The discovered IR object which has been previously identified as a variable star shows a prominent mid-IR excess, indicating the presence of a dust shell. This along with the strong Hα emission makes the suggestion that this object may be a low-mass Cepheid rather unlikely. We suggest instead that this object may be a low mass field post-AGB star in a proto-planetary nebula stage or a Be supergiant belonging to cluster NGC 330. In both cases the expected optical extinction is relatively high ($A_V \sim 2.0-2.5$). We also can not reject the possibility that this object may be an isolated Herbig Ae/Be star. Unfortunately, presently available observations do not allow to distinguish between these scenarios clearly. Neither the basic stellar parameters of the detected object, nor the physical conditions in the Hα and dust emitting regions can be constrained precisely yet. Therefore, further photometric observations in the UV, near-IR and far-IR, and especially optical spectroscopy would be a highly desirable second step towards clarifying the nature of MIR1.

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